Conversion of Waste CO_2 & Shale Gas to High Value Chemicals

DE-EE0005766
Novomer, Inc. (Praxair Sub-Contractor)
Project Period: 8/1/2013-11/30/2015

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Project Objective

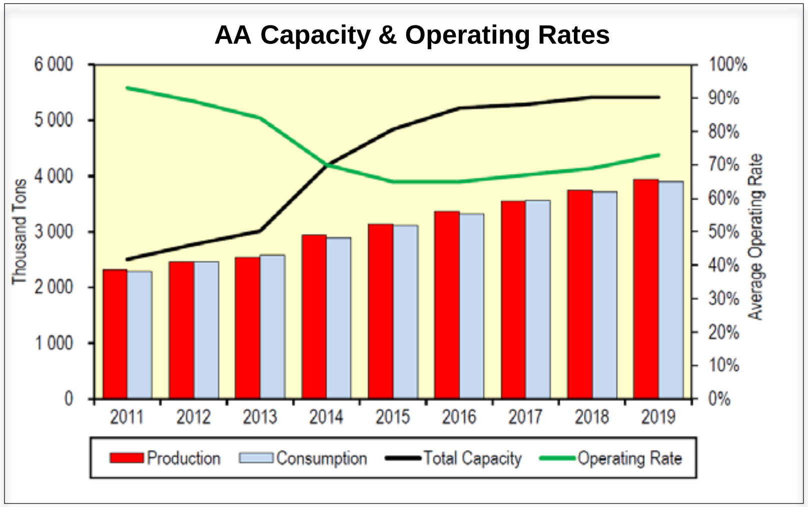
- Overall Objective – To develop, build, and validate a semi-integrated laboratory scaled continuous process with capacity of 5kg/day to make CO_2-based drop-in chemicals.
- Achieve industry leading cost for Acrylic Acid, Succinic Anhydride, and Propiolactone based polymers
  - Novomer process can leverage lower cost ethylene feedstocks from shale and other sources
  - Lowest capital cost due to simple unit operations
- Low Carbon & Energy Footprint
  - >99% catalyst selectivity results in high atom efficiency and almost zero wasted feedstock.

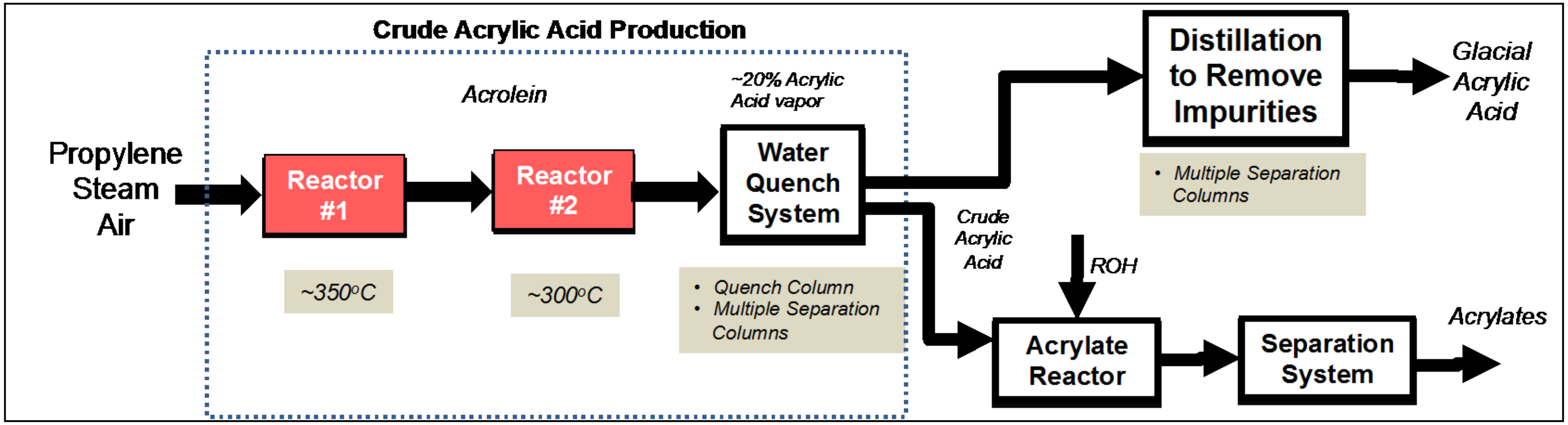
Technical Approach

- The current propylene oxidation process to make **Acrylic Acid** (AA) is energy intensive and has operating challenges.

<u>Characteristics of Existing Propylene Process</u>

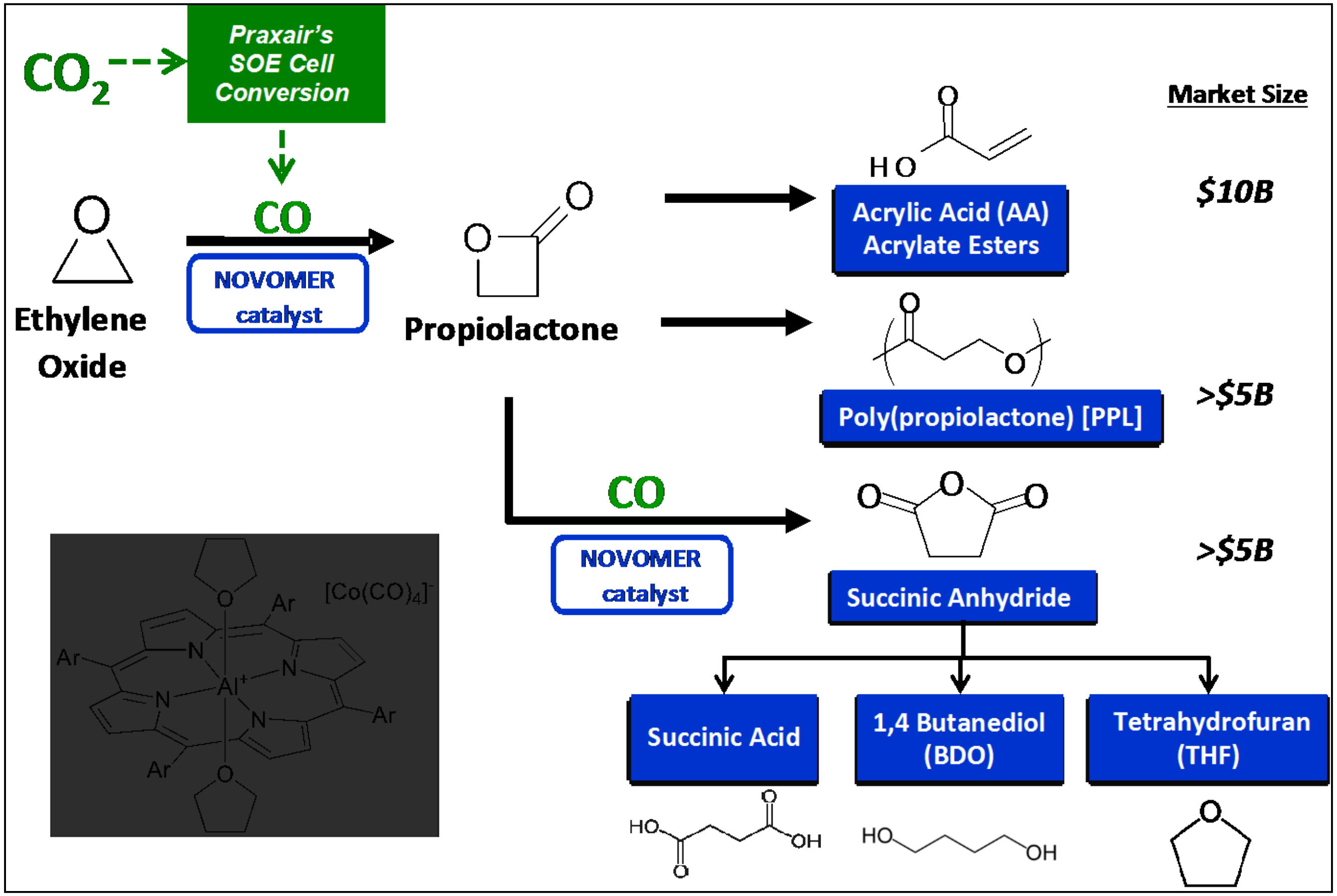
- Complex, expensive reactors
    - Molten salt cooling system
- Sensitive catalytic systems
- Difficult downstream separation
- Energy intensive process
- Global operating rates (60-70%) significantly below industry average (graph inset)





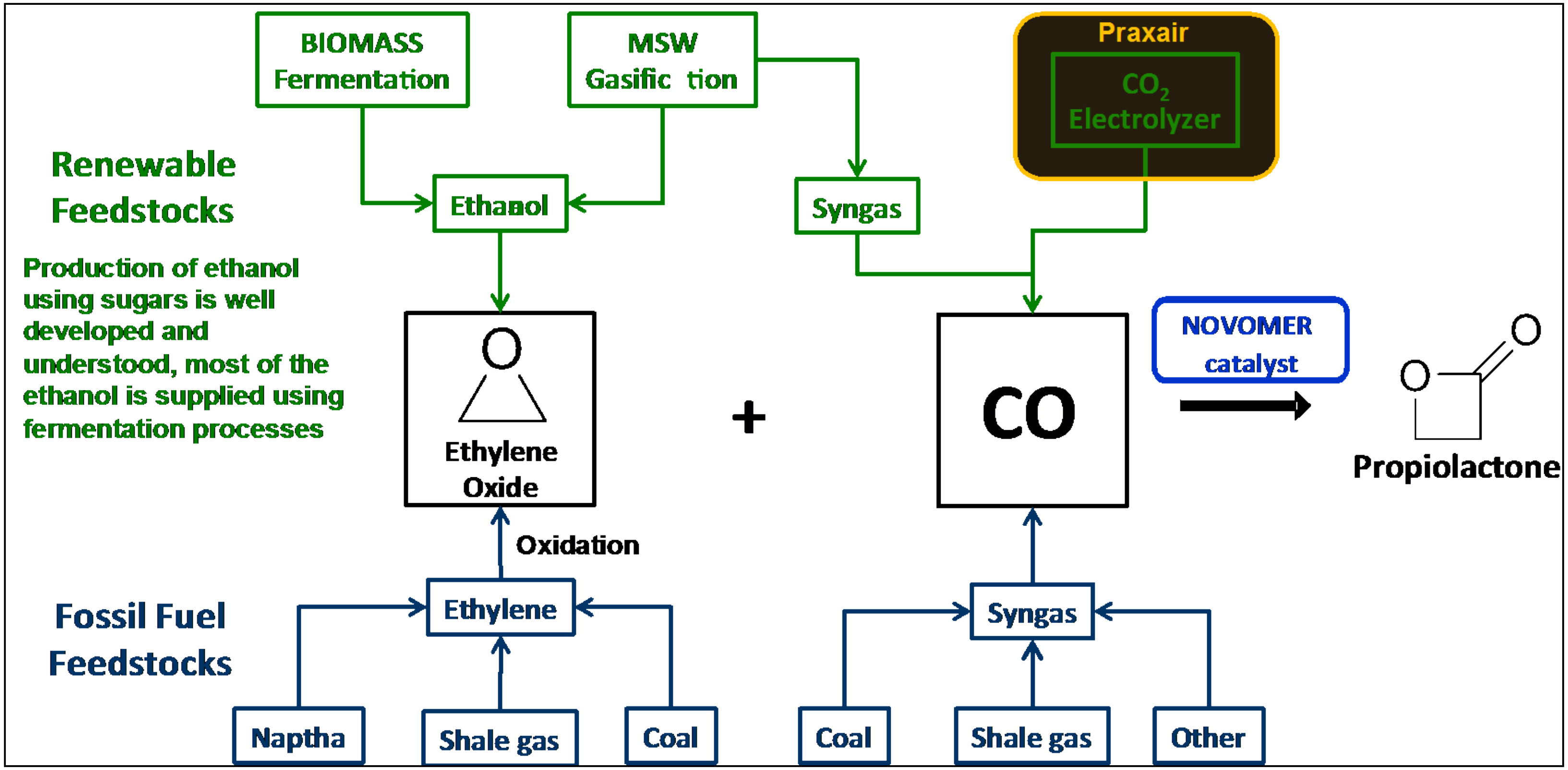
Technical Approach

- Advantages of Novomer Process:
  - High Selectivity Catalyst (>99%)
  - Leverages low cost shale gas & ethylene derivatives
  - Lower energy & carbon footprint
  - Novomer process changes the paradigm with respect to transporting Glacial AA



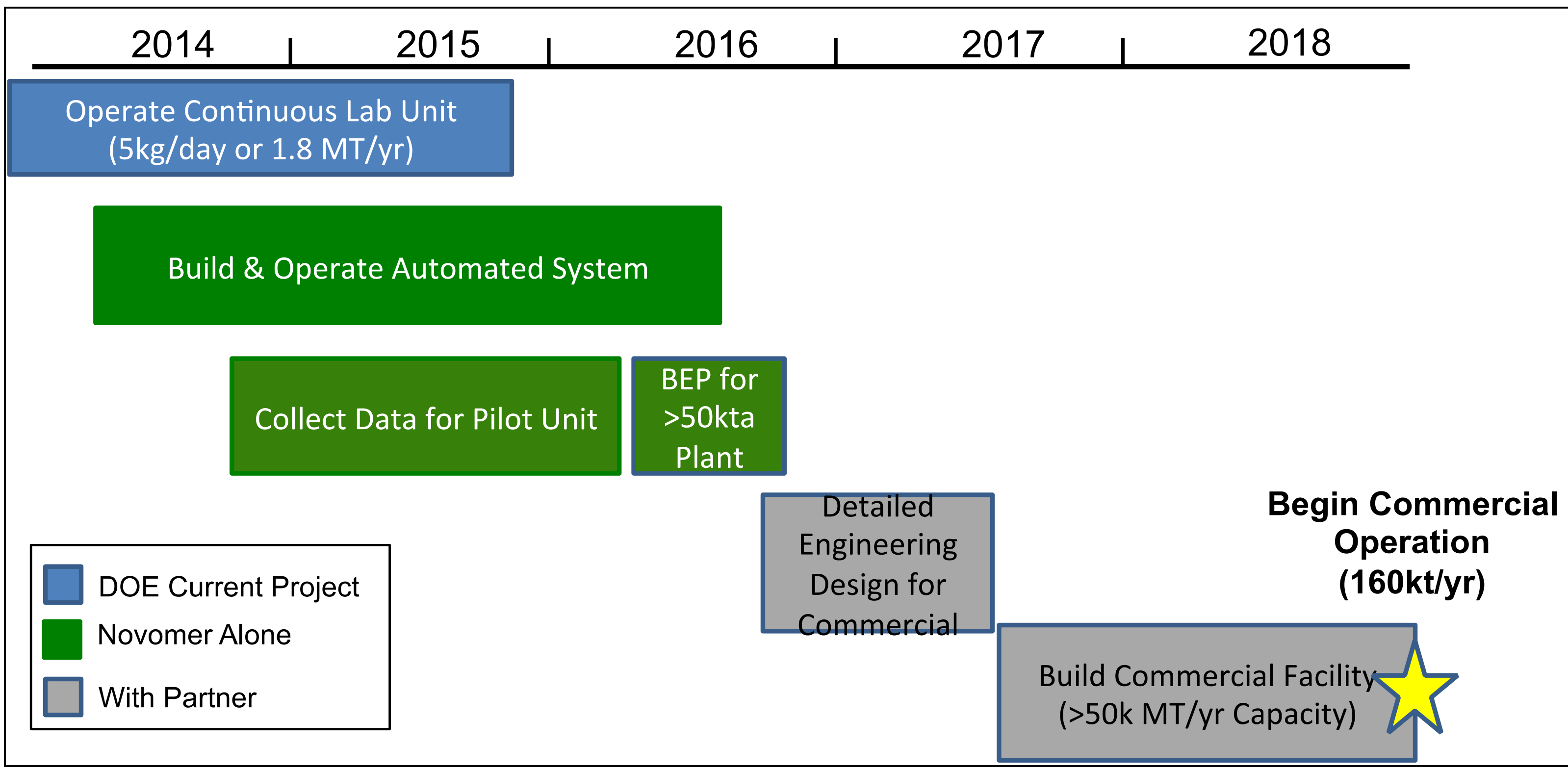
Transition and Deployment

- Novomer process is feedstock agnostic & appeals to a wide range of chemical & brand companies for deployment
  - Brand owners interested in carbon negative AA from bio-based sources
  - Chemical manufacturer with low cost ethylene feedstock interested in higher value derivatives and diversification.



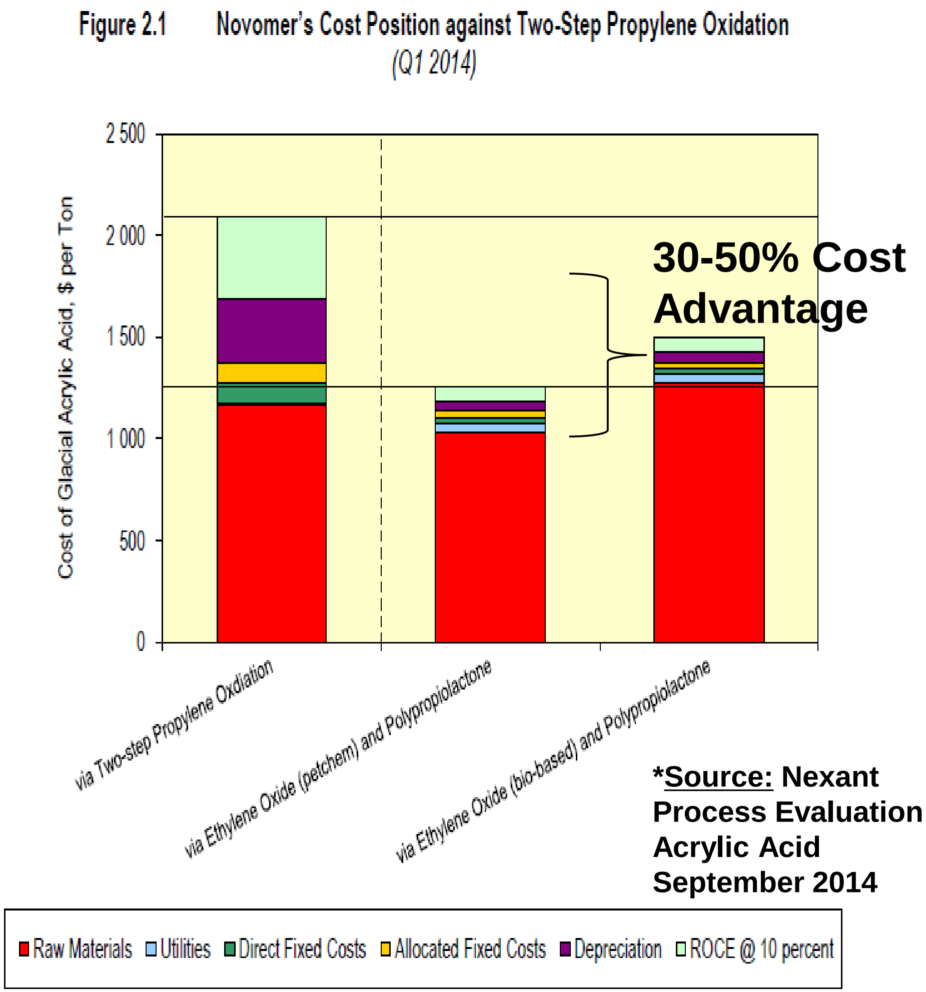
Transition and Deployment

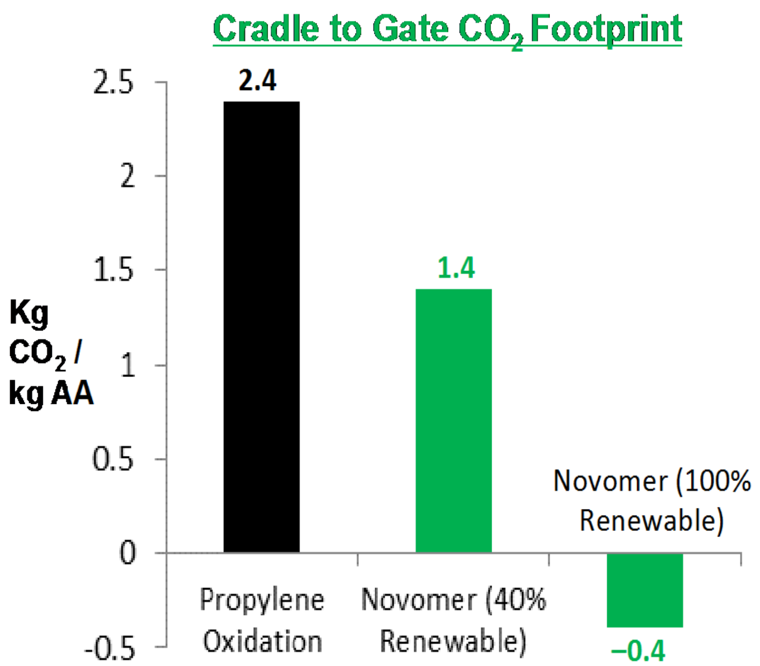
- Novomer has started the BEP for a >50kt/yr commercial plant.
- First commercial plant will be ready for production at end of 2018.



Measure of Success

- Novomer's process will be 30-50% lower cost and have a significantly lower carbon & energy footprint.





Project Management & Budget

- Project Duration – Aug 1 2013 to Nov 30 2015
  - BP1 – All Tasks Complete
  - BP2 – All Tasks Complete.

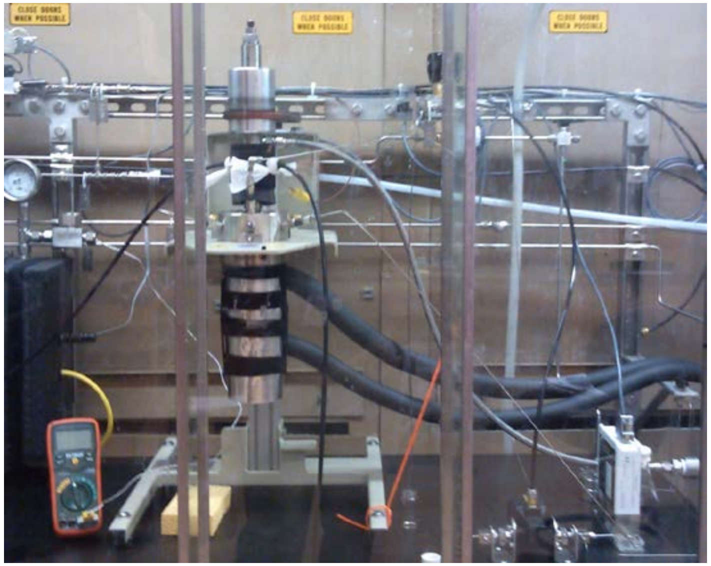
Total Project Budget	
DOE Investment	$4.3M
Cost Share	$1.6M
Project Total	$5.9M

	SOPO Task	Complete
Budget Period (BP) 1	Task 1 – Evaluate, Build, & Test Major Carbonylation Unit Operations	✓
	Task 2 – Preliminary Economics & LCA	✓
	Task 3 – SOE Cell Test Infrastructure & Materials Development	✓
	Task 4 – Project Management & Reporting	✓
BP 2	Task 5 – Integrate Lab Scale Continuous Process	✓
	Task 6 – Combustion Assisted CO_2/CO Electrolysis Cell Testing	✓
	Task 7 – Develop Robust Catalyst Synthesis	✓
BP 3	Task 10 – Finalize & Validate Carbonylation Process	✓

Results and Accomplishments

Major Accomplishments

- Determined optimal reactor configuration
  - Built & Tested 3 Different reactor configurations (Single phase CSTR, two phase CSTR, and Loop Reactor)
- Identified separation scheme for Catalyst
  - Evaluated membrane, liquid/liquid extraction, and distillation
- Dramatic Improvement in Catalyst Performance
  - Improved catalyst activity by 3X, Reduced solvent cost by 1/2, and improved solubility by 5X
- Validated Economics, Energy, and CO_2 Footprint
  - Third parties (CCTI & Nexant) provided external validation
- Operated Continuous System with recycle for extended periods of time.



Reactor System (Rochester, NY)

Exceeded Go/No-Go Metrics

	BP1 Goal	Achieved
Selectivity	95%	>99%
Residence Time	<600 min	40 min
Lactone Concentration	>15wt%	30wt%
Catalyst Rejection	>80%	99.5%
EO Conversion	>60%	>95%

Addendum –

- Novomer has made significant investment in parallel with the DOE Project
- Designed, built, and commissioned an automated continuous system in Q4 2014.
- Complimentary to Current DOE Project; Allows technology to be scaled more quickly.